

Changes in the capacity of visual working memory in 5- to 10-year-olds

Kevin J. Riggs^{a,*}, James McTaggart^a, Andrew Simpson^a,
Richard P.J. Freeman^b

^a *Department of Psychology, London Metropolitan University, London E1 7NT, UK*

^b *Institute of Education, University of London, London WC1H 0AL, UK*

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Abstract

Using the Luck and Vogel change detection paradigm, we sought to investigate the capacity of visual working memory in 5-, 7-, and 10-year-olds. We found that performance on the task improved significantly with age and also obtained evidence that the capacity of visual working memory approximately doubles between 5 and 10 years of age, where it reaches adult levels of approximately three to four items.

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Introduction

There is strong evidence that performance on visual working memory tasks improves throughout childhood. For example, Wilson, Scott, and Power (1987) presented 5-, 7-, 11-, and 35-year-olds with matrices in which half of the squares were filled in black. These were then redisplayed with one square missing, and participants were asked to point to the location of change. The amount of information to be remembered in the task was manipulated by using more complex matrices involving more black squares or white spaces. It was found that older children could point out changes in more complex matrices, reaching

* Corresponding author. Fax: +44 20 7320 1236.

E-mail address: k.riggs@londonmet.ac.uk (K.J. Riggs).

adult levels of performance by approximately 11 years of age. Age-related changes in performance have also been found using *n*-back recall tasks, where children were required to recall the identities of serially presented pictures. Older children were able to recall sequences further back in the series (e.g., Vuontela et al., 2003).

It is not clear whether performance improvements are related to a growth in visual working memory capacity or to the use of verbal coding and other strategies. Evidence is mixed. Older children seem to be unable to reduce the proportion of visual information they lose from memory over time, suggesting that rehearsal strategies are of little help in matrix tasks (Walker, Hitch, Doyle, & Porter, 1994). A study that took steps to minimize verbal coding still found a strong developmental pattern in memory for visual objects presented serially (Walker et al., 1994). In contrast, Hitch, Woodin, and Baker (1989) showed that older children will use verbal strategies on visual tasks whenever possible.

The Luck and Vogel change detection paradigm

Recently, Luck and Vogel (1997) and Vogel, Woodman, and Luck (2001) devised a visual memory task to assess visual memory capacity in adults. In a change detection paradigm, participants were given a brief, but above-threshold, presentation of a sample array of colored squares (arrays varied in size from 1 to 12 squares). After a blank interval, the array was presented again. On half of the trials, the test array was identical to the sample array. For the other trials, a randomly chosen square changed color. Participants judged whether a change had taken place with a premium on accuracy rather than speed. Vogel and colleagues (2001) varied the number of squares in the array, the duration of first presentation, and the interstimulus interval. They reasoned that if the first presentation is sufficiently brief, then verbal coding is less likely to be used or to be helpful as a strategy—an assumption supported by the fact that performance on the task was not significantly affected by a concurrent verbal load.

Performance on the task by adults was near ceiling for arrays with up to two squares, declined slightly for arrays of three and four squares, and declined more sharply thereafter as array size increased. One interpretation is that the adult visual memory buffer has a capacity for up to approximately four items, after which it becomes overloaded. A simple probabilistic model for change detection (Pashler, 1988) extends and quantifies this argument. If a participant can, in general, encode k objects in visual working memory simultaneously, then performance should be at or near ceiling for arrays of up to k squares. For n squares (where $n > k$), however, the participant has only k of n chances of encoding the target square (the one that will change) and thus will show asymptotically decreasing accuracy as the number of squares increases beyond k . The model can be refined to reflect guessing by using the number of “false alarms” (i.e., no-change trials on which the participant claims to have seen a change) as a measure of individual propensity to guess at each array size. If h is the proportion of correct judgments and g is the probability of guessing, then the model becomes $h = g + (1 - g) \times (k/n)$. Using this equation, Vogel and colleagues (2001) found an average visual memory capacity limit for adults of between three and four items.

Investigating developmental capacity increases

The Luck and Vogel (1997) task offers the possibility of investigating visual working memory capacity in children of different ages because it controls for verbal coding

strategies. In fact, a version of the technique has already been attempted with very young children (Ross-Sheehy, Oakes, & Luck, 2003). Infants were presented with two computer monitors on which two simultaneous displays of colored squares blinked on and off. On one monitor one color was changed in each new presentation, while on the other monitor the colors remained constant. The dependent measure was the amount of time infants spent looking at the different displays, with the assumption that infants would look longer at the more interesting stimulus. The logic of the experiment was that, to find the changing display more interesting, infants would need to notice the changes, thereby giving a measure of how many colored squares they can encode simultaneously. With controls for perceptual and attentional abilities, the findings suggested development in visual working memory during the first year of life. Until approximately 6 months of age, infants showed no sign of change detection for arrays with more than one square. However, 10-month-olds showed preferences for the changing displays for two and four squares but not for six squares. Ross-Sheehy and colleagues (2003) suggested that visual working memory capacity for objects increases during the first year of life to the adult level of approximately four items.

However, there are grounds to doubt this conclusion. As one reviewer pointed out, it does not follow from the fact that infants noticed changes in an array of size X that they held X items in working memory. Children need not have noticed every change in the change condition to discriminate it from the no-change condition. Merely focusing on a single item in the change array and seeing it change on a proportion of trials may have been sufficient for discrimination.

More recently, convincing evidence has been reported to suggest that the capacity of visual working memory changes during childhood. Cowan and colleagues (2005) tested children and adults on a variant of the Luck and Vogel (1997) paradigm and found changes in capacity between 8-year-olds and adults. In their study, the initial array was presented for 250 ms, followed by a blank screen for 900 ms and then the test array with one of the squares encircled. Participants needed to judge whether this “cued” square had changed color. They found evidence for a capacity increase from approximately two items in 8-year-olds to four items in 11-year-olds. However, it is possible to argue that the youngest children performed worse than the older children and adults because (a) the youngest children had difficulty in following the instructions in the cued condition and (b) they had difficulty in encoding information from the initial array in such a short space of time (250 ms).

Given the inconsistent interpretations concerning visual working memory capacity in the literature, we thought it was necessary to further investigate the claims of Cowan and colleagues (2005) for changes in capacity during childhood. We made three changes to the methods of Cowan and colleagues’ study. First, we tested younger children, thereby extending the age range from 5- to 10-year-olds. Second, we used the standard “noncued” Luck and Vogel (1997) change condition, with the aim of making the task instructions as easy as possible for the youngest children. Finally, we increased the presentation time of the initial array from 250 to 500 ms to give the youngest children more time to encode the visual information presented. We were keen to ensure that these children had enough time to encode as much information as they had capacity for without providing so much time that the older children used rehearsal and/or other verbal strategies. For this reason, we chose a duration of 500 ms. Vogel and colleagues (2001) varied the time of presentation of the initial array from 100 to 500 ms and found no difference in performance.

Method

Design

The experiment used a partially repeated-measures factorial design. The between-participants factor was age (5-, 7-, or 10-year-olds). Each participant contributed judgment scores for each of five levels of the within-participants factor, stimulus array size. Stimuli consisted of one, two, three, four, or five colored squares.

Participants

A sample of 60 children was drawn from two urban primary schools in Glasgow, Scotland. There were 20 5-year-olds (11 boys, mean age = 5 years 6 months, and 9 girls, mean age = 5 years 7 months), 20 7-year-olds (10 boys, mean age = 7 years 3 months, and 10 girls, mean age = 7 years 3 months), and 20 10-year-olds (8 boys, mean age = 10 years 6 months, and 12 girls, mean age = 10 years 9 months). All participants were reported as having normal color vision and normal or corrected-to-normal visual acuity.

Materials

Stimuli were presented on the LCD screen of a Sony Vaio laptop within a $9.8 \times 7.3^\circ$ region with a light gray background. Participants viewed stimuli from a distance of 60 cm. Stimulus arrays consisted of one, two, three, four, or five colored squares. Each square was placed randomly within this region, with the constraint that items in a given array were separated from each other by a minimum of 2° from center to center. The color of each square was drawn randomly (with replacement) from a set of six colors: red, orange, green, purple, blue, and dark gray. Each square subtended $0.65 \times 0.65^\circ$ of visual angle. As in Vogel and colleagues' (2001) study, a given color could occur more than once in an array and the color of a changed item sometimes was the same as the color of another item in the array; for example, in an array with two squares, the probability of the "second" square color being the same color as the first was 1/6. Thus, correct performance required the encoding of the colors of the individual squares rather than just a list of colors present in the array.

Procedure

For training, the participants were first shown a sheet of white A4 paper on which there were four 1.5-cm^2 squares colored red, blue, yellow, and green. The participants were asked to name the colors both to raise the salience of color discrimination and to confirm that they could easily discriminate the colors. They were then shown another sheet of paper identical to the first except that the red square had been replaced with a blue square. Many participants, with little or no prompting, offered the observation that the sheets were different because one square was a different color. The procedure was repeated with another pair of sheets, but this time with no color change.

Children were then informed that the computer would display some colored squares very quickly and that the squares would vanish and then return. Children were also told that the game was to spot correctly when a square had changed color and when all squares stayed the same color.

A practice program was then run, where participants were talked through the change detection paradigm in slow motion, with array sizes of up to three squares. Participants did not proceed to the experiment proper until they were successful on the practice program. Only four children needed more than one practice run, and none needed more than two practice runs.

The experiment ran in five blocks of 12 trials each. Within each block, stimuli consisted of the same number of squares to minimize possible effects of confusion in the children. The order of blocks was randomized to control for practice effects, with the exception that the youngest children always began with one or two square trials to make sure they had grasped the procedure.

Each trial consisted of a sample array of colored squares being presented for 500 ms, followed by a 900-ms blank delay and then a test array that remained for 3000 ms or until the participant responded. On half of the trials, the sample and test arrays were identical. On the other half of the trials, the sample and test arrays differed in that one random square randomly changed color. The participant indicated whether he or she thought the test array was different from or the same as the sample array, and the experimenter entered the answer on the keyboard. There was a short pause between each block of trials for the participant to rest.

Results

For each array size, each participant contributed six judgments on trials in which one of the presented squares changed color and six judgments on trials in which there was no color change. The time taken to record each judgment was also recorded. Thus, each participant, for a given array size, obtained two scores out of six: one for change trials and one for no-change trials.

Developmental trends

The mean percentages of correct responses on change trials for each age group and array size are presented in Fig. 1. It can be seen that mean performance on the task improved with age and that, for all age groups, mean performance decreased as array size increased. This decrease was most marked for the youngest children and least so for the oldest children.

Performance was analyzed in a repeated-measures analysis of variance (ANOVA) with array size (one, two, three, four, or five squares) as the within-participants factor and age group (5-, 7-, or 10-year-olds) as the between-participants factor. There was a main effect for array size, $F(1, 57) = 50.90$, $p < .001$, $\eta^2 = .47$, and for age group, $F(2, 57) = 29.85$, $p < .001$, $\eta^2 = .51$. There was also a significant interaction between array size and age group, $F(2, 57) = 6.21$, $p = .004$, $\eta^2 = .30$.

Further analysis using Tukey's post hoc tests investigated whether there were significant differences between the performances of different age groups at different array sizes. The performance of 5-year-olds was significantly different from that of 10-year-olds with all array sizes (one square, $p = .04$; two squares, $p = .002$; three squares, $p < .001$; four squares, $p < .001$; five squares, $p < .001$) but diverged significantly from that of 7-year-olds only with four squares, $p < .001$, and five squares, $p = .034$. The performance of 7-year-olds diverged from that of 10-year-olds only with four squares, $p = .049$.

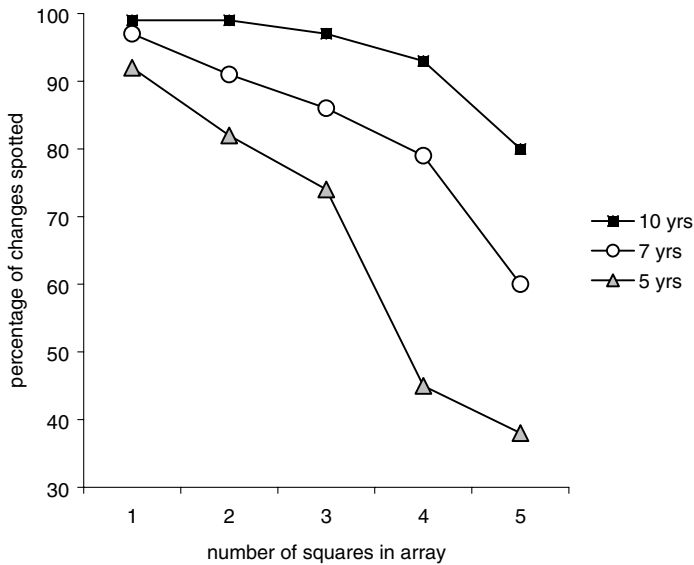


Fig. 1. Mean percentages of changes detected by each age group at each array size.

Within age groups, the performance of 10-year-olds with five squares was significantly different from that with four squares, $t(19) = 2.49$, $p = .02$. For 7-year-olds, performance was significantly different between three squares and five squares, $t(19) = 3.69$, $p = .002$, and between four squares and five squares, $t(19) = 2.97$, $p = .008$, but not between three squares and four squares. For 5-year-olds, significant differences were found between one square and two squares, $t(19) = 2.259$, $p = .036$, and between three squares and four squares, $t(19) = 5.044$, $p < .001$.

A capacity-based model for performance

Using the Pashler (1988) model, $h = g + (1 - g) \times (k/n)$, where h is the proportion of correct judgments and n is the array size, we computed capacity estimates (k) for each age group. One complication we noticed is that the guessing rate (g) may well vary with both age and memory capacity. Someone with a capacity of one slot clearly will have more occasions to guess on trials with three squares than will another individual with four slots. Therefore, we computed separate values of g for each age group. Across all age groups, the guessing rate was not high. As one might expect, younger children on the whole guessed more (11%) than older children (3%), and the guessing rates increased as array size increased. Using this model, we obtained visual working memory capacity estimates of 1.52 items for 5-year-olds, 2.89 items for 7-year-olds, and 3.83 items for 10-year-olds.

General discussion

Overall, children's performance on the task improved with age, and children had more difficulty in identifying changes with larger array sizes. These findings are consistent with previous research providing evidence for age-related improvements in performance on visual working

memory tasks (e.g., Cowan et al., 2005; Logie & Pearson, 1997; Pickering, Gathercole, Hall, & Lloyd, 2001; Vuontela et al., 2003; Wilson et al., 1987). Our findings also provide support for the view that performance improvements reflect a capacity increase in visual working memory. The capacity for 10-year-olds is consistent with the estimate for adults of three to four items provided by Vogel and colleagues (2001) and Cowan and colleagues (2005). Other visual memory studies have also found that when children reach 10 or 11 years of age, they perform at adult levels (e.g., Logie & Pearson, 1997; Wilson et al., 1987).

Our findings are also consistent with the finding of Cowan, Nugent, Elliott, Ponomarev, and Saults (1999) that verbal memory capacity approximately doubles in size from two items in 5- to 7-year-olds to four items in 11-year-olds and adults.

How do our results relate to those reported by Ross-Sheehy and colleagues (2003), which can be taken to suggest that infants have a visual working capacity for up to four items by the end of their first year? As mentioned earlier in this article, there are grounds for doubting that their data measure visual working memory capacity. Another explanation is that the task with infants is a passive task and does not tap into the same kind of purposive working memory processes as measured by the Luck and Vogel (1997) paradigm. Finally, it might be that visual working memory capacity is fixed during infancy and that the findings of the current study are due to factors other than a change in capacity. In what follows, we discuss some of these possible factors.

Differences in perception and attention

One possibility is that younger children miss more changes because of simple attentional lapses. The procedure demands sustained attention and concentration across 10 to 12 min of testing and short lapses might easily lead to errors. However, the task was paced individually for each child with rests available. The pretasks seemed to be successful in establishing an understanding of the change detection paradigm, and all children seemed to engage throughout.

Another possibility is that our results reflect age-related processing differences in the rate at which items can be encoded into visual working memory. Vogel and colleagues (2001) showed that adults have no difficulty in encoding four squares in a presentation time of 100 ms. On the slowest estimate, from a serial encoding mechanism, this allows 25 ms per item. A presentation time of 500 ms allows children 125 ms, or five times as long, per item. Therefore, on the basis of the current results, if 5-year-olds can encode only two items in 500 ms, then this suggests a 10-fold developmental increase in speed of processing between 5 and 10 years of age. This seems extravagant. Evidence suggests that processing speed does indeed improve between the ages reported here, but not by a factor of 10 (Kail, 1991). Moreover, encoding is likely to be more rapid than this because it is likely to take place at least partly in parallel (Jolicoeur & Dell'Acqua, 1998; Magnussen, Greenlee, & Thomas, 1996). Therefore, we think it is unlikely that a difference in speed of processing at encoding accounts for the differences in performance between the 5- and 10-year-olds. A more plausible suggestion is that the capacity of visual working memory changes over that period.

Strategies and verbal recoding

It is possible that in our task some verbal coding may have taken place, with children internally naming the colors of some or all of the squares in the array. However,

Vogel and colleagues (2001) provided evidence that performance on their task is not assisted greatly by verbal recoding of the colored squares (a result replicated by Fencsik, 2003). We think it is unlikely that children, with such a brief presentation, could have verbalized and then rehearsed the color names of more than one or two squares.

However, older children will use verbal strategies to enhance visual memory where possible (Hitch et al., 1989), and the current study may have allowed this by using a longer initial presentation time (500 ms) than that used in the majority of trials by Vogel and colleagues (2001). Therefore, the use of verbal recoding to enhance the performance of older children cannot be ruled out with certainty. The issue could be resolved by giving older children a concurrent articulatory suppression task to impede verbal recoding. This was not investigated in the current study, where the aim was a comparison with 5-year-olds, whose attention on the primary task might well have been impeded by a difficult (for them) concurrent language task. However, even if the current capacity estimate for 10-year-olds is inflated by verbal strategies, Vogel and colleagues' data suggest that the capacity in adults is not inflated by such strategies. We are still left with strong evidence for a capacity change in visual working memory between 5-year-olds and adults.

In conclusion, the current study offers further evidence that performance on visual working memory tasks improves with age. It also provides evidence, based on a simple model, that these improvements are at least partly mediated by an increase in capacity. Thus, the Luck and Vogel (1997) paradigm is a useful tool for exploring the development of visual working memory, and extending its applications will likely cast further light on this topic of investigation.

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